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Artigo de Pesquisa

Morphotectonic and morphostructural investigation in northwestern Minas Gerais State, Brazil: a lineament mapping assessment

Investigação morfotectônica e morfoestrutural no Noroeste do Estado de Minas Gerais, Brasil: uma avaliação a partir do mapeamento de lineamentos

Mário Teixeira Rodrigues Bragança [1], Luiz Fernando de Paula Barros [2], Déborah de Oliveira [3]

[1] Programa de Pós-Graduação em Geografia Física, Faculdade de Filosofia, Letras e Ciências Humanas, Universidade de São Paulo, São Paulo, Brasil. *Current address*: Secretaria Municipal de Educação, Prefeitura Municipal de Betim, Betim, Brasil. E-mail. mario.teixeira@alumni.usp.br
ORCID: https://orcid.org/0000-0003-2729-3619

[2] Departamento de Geografia, Programa de Pós-Graduação em Geografia, Instituto de Geociências, Universidade Federal de Minas Gerais, Belo Horizonte, Brasil. E-mail. luizbarros@ufmg.br
ORCID: https://orcid.org/0000-0001-6122-4778

[3] Departamento de Geografia, Programa de Pós-Graduação em Geografia Física, Faculdade de Filosofia, Letras e Ciências Humanas, São Paulo, Brasil; Programa de Pós-Graduação em Rede Nacional para Ensino das Ciências Ambientais, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brasil. E-mail. debolive@usp.br
ORCID: https://orcid.org/0000-0002-3679-2893

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Abstract: This study aimed to investigate whether linear natural features are associated with structural or tectonic control of landforms and current drainage patterns in northwestern Minas Gerais State (Southeastern Brazil). To answer this question, more than 1,700 lineaments were manually mapped in a broader area encompassing the Paracatu and Urucuia River catchments. One satellite image scene (Operational Land Imager/Landsat-8), three different digital elevation models (Shuttle Radar Topography Mission, Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global digital elevation model, and Advanced Land Observing Satellite-Phased Array L-band Synthetic Aperture Radar), and digitised analogical maps (geologic and topographic maps) were used to draw linear geometric features representing the lineament population. The resulting vector databases were integrated in a Geographic Information System for quantitative and spatial analyses, which resulted in two main trending lineament sets: NNW-SSE and NE-SW. Subsequent field assessments revealed that numerous lineaments from the first set were correlated to the formerly Upper Precambrian reverse and strike-slip faults. The second set were correlated to NE-SW normal faults derived from the Mesozoic-Cenozoic tectonic event following the breakup of Gondwana. These datasets contribute to a better understanding of the regional-, sub-regional-, and catchment-scale features underlying the structural control of the drainage network arrangement and pattern, which present long straight channels and are interrupted by anomalous and prominent bends that strictly fit major structural directions.

Keywords: Lineaments; Structural landforms; Drainage pattern; Morphostructure; Morphotectonics.

Resumo: Este estudo investigou se feições naturais lineares estão associadas ao controle estrutural ou tectônico de formas de relevo e padrões de drenagem atuais no Noroeste do Estado de Minas Gerais (Sudeste do Brasil). Para responder a essa pergunta, mais de 1.700 lineamentos foram mapeados manualmente em uma área abrangendo as bacias hidrográficas dos rios Paracatu e Urucuia. Uma cena de imagem de satélite (OLI/Landsat-8), três diferentes modelos digitais de elevação (MDE;

SRTM, GDEM-ASTER e ALOS-PALSAR) e mapas analógicos digitalizados (geologia e topografia) foram usados para o mapeamento de feições geométricas lineares, representando a população de lineamentos. As bases de dados vetoriais resultantes foram integradas em GIS para análises quantitativas e espaciais, resultando em dois principais conjuntos de lineamentos de orientações NNW-SSE e NE-SW. As subsequentes avaliações de campo revelaram que numerosos lineamentos do primeiro conjunto se correlacionam a falhas inversas e transcorrentes do Proterozoico Superior. O segundo conjunto refere-se a falhas normais NE-SW associadas ao evento tectônico Mesozoico-Cenozoico e à fragmentação do Gondwana. Esses conjuntos de dados contribuem para uma melhor descrição e compreensão dos controles estruturais sobre a rede de drenagem, nas escalas regional, sub-regional e de sub-bacia, que se manifestam em longos canais retilíneos interrompidos por curvas anômalas e pronunciadas; essas feições encaixam-se estritamente nas duas direções estruturais indicadas.

Palavras-chave: Lineamentos; Formas estruturais; Padrão de drenagem; Morfoestrutura; Morfotectônica.

1. Introduction

Numerous studies have shown that continental palaeodrainage systems mirror the importance of the structural background in the recent geomorphic evolution of African and South American drainage systems (XAVIER et al., 1976; POTTER, 1987; COX, 1989; RIBEIRO et al., 2018), which exhibit important similarities. One reason for the observed similarities is that from the Meso-Cenozoic period until the Early Miocene period, a general tilting toward the north was observed in uplift-prone southern parts of both continents, such as in the Andean Chain (GIAMBIAGI et al., 2016), Atlantic and Central Brazilian Plateau, São Francisco Craton (SAADI, 1991; VALADÃO, 1998), Serra do Mar and Brazilian Atlantic Passive Margin (XAVIER et al., 1996), and Central and West Africa (SIEDNER; MITCHEL, 1976; MOORE; LARKIN, 2001; GOODIE, 2005).

The São Francisco Craton (ALMEIDA, 1977) runs along the eastern Mantiqueira and western Tocantins Precambrian orogenic systems and is roughly parallel to the Atlantic coast, and it extends from southern Minas Gerais to southern Piauí states in Brazil. During the Mesoneoproterozoic PanAfrican-Brazilian orogenic events (HEILBRON et al., 2000), the São Francisco Craton was part of the greater Late Upper Proterozoic São Francisco-Congo-Kalahari craton (HASUI, 2010), which is a Gondwanide continental block that originally extended east into South Africa and south into Antarctica (HASUI, 2010). With the Mesozoic break up (TROMPETTE et al., 1992), South America and Africa drifted apart in the Valanginian (LARSON; LADD, 1973; SIEDNER; MITCHEL, 1976), probably because of Cretaceous hot spots (ULBRICH; GOMES, 1981; THOMAZ FILHO; RODRIGUES, 1999; WHITE; MCKENZIE, 1989), which led to doming, uplift, as well as rifting processes and ultimately caused continental fragmentation (ALMEIDA 1976; SIEDNER; MITCHELL, 1976; COX, 1989).

Regional structural settings have been assessed as a background for morphological and morphotectonic investigations, usually as frameworks for either small geomorphic features or subcontinental landform landscapes (MCKEOWN et al., 1988; ALVES; CASTRO, 2003; SALAMUNI et al., 2004; DEMOULIN et al., 2017). These structures are elements of the landscape resulting from crustal deformation (MANJORO, 2015) and control the dynamics of landforms and river patterns through active or passive folds, faults, joints, foliations, schistosity, bedding, stratigraphic rock strata distribution, and other geological features (SARTORATO, 1998). Streams respond directly to structural controls and are commonly guided by faults, lineaments, and topographic ruptures, which reflect the characteristic aspects of the geomorphic landscape (ALVES; CASTRO, 2003; MANDJORO, 2015).

Lineament mapping methodologies that apply multiple remote sensing products have been used to generate preliminary and exploratory terrain maps for geological (PARANHOS FILHO et al., 2013), geomorphological (CORREA; FONSÊCA, 2010), tectonic (FORTES et al., 2007; BEŇÁK; SILVA, 2017), structural (KOÇAL, 2004), hydrological (REGINATO; STRIEDER, 2002), and mineral (SARTORATO, 1998) purposes. Particularly, the density and directional patterns of crustal lineaments and the associated drainage network support the morphometric analytical description of the surficial morphological texture (SILVA et al., 2007). Therefore, crustal lineament features in the western São Francisco Craton and adjacent areas of the Brasilia Mobile Belt were mapped to assess whether linear natural features are associated with structural or tectonic control of landforms and current drainage patterns on two scales (the regional Paracatu and Urucuia Rivers catchments and the local Cotovelo River catchment). The main regional fault pattern of the western São Francisco Craton, the western termination of the Brazilian Atlantic shield, is largely known and characterised (ALMEIDA, 1977; ALKMIM et al., 1993; ALKMIM; BRITO-NEVES, 1993; CAMPOS; DARDENNE, 1997b; ALKMIM, 2004). Therefore, this research focused on mapping lineaments at large and regional scales as well as small scales, and it then identified correlations in morphology based on spatial and geological contexts. This correlation analysis represents a suitable approach for investigating the degree of interference of these lineaments in the morphogenesis of the region, which was interpreted based on the correlations between structure and geomorphology.

1.1 Study area

This investigation was conducted in two study areas for data collection and assessment (Figure 1). The first evaluated area was represented by a rectangular perimeter that encompassed the Paracatu and Urucuia River catchments and their tributaries (Figure 1A) and included the natural extension of the investigated features, namely, landforms, river channels, and lineaments. Moreover, this area supports a better assessment of the superimposition of the investigated regional structures on the drainage network elements. The Paracatu and Urucuia Rivers are major left bank tributaries of the São Francisco River, which is the largest Brazilian river that drains into the Atlantic Ocean along the northeastern coast of Brazil. Geographically, the regional study area is delimited by the south latitudes Y1:7,934,000 to Y2:8,297,000 and west longitudes X1:219,000 to X2:501,000 (WGS84 – UTM zone 23), and it covers approximately 108,000 km² (Figure 1B).

The second spatial extent included the Cotovelo River catchment, which is a left-bank tributary of the Paracatu River with an area of 788.1 km². This catchment is located on the western border of the Brazilian Atlantic Shield and lies entirely in the western-deformed São Francisco Craton foreland basin coverage (ALKMIM et al., 1993). This area is delimited by the south latitudes Y1:8,112,000 to Y2:8,155,000 and west longitudes X1:382,000 to X2:421,000 (WGS84 – UTM zone 23), and it forms a block that covers approximately 1,670 km² (Figure 1C).

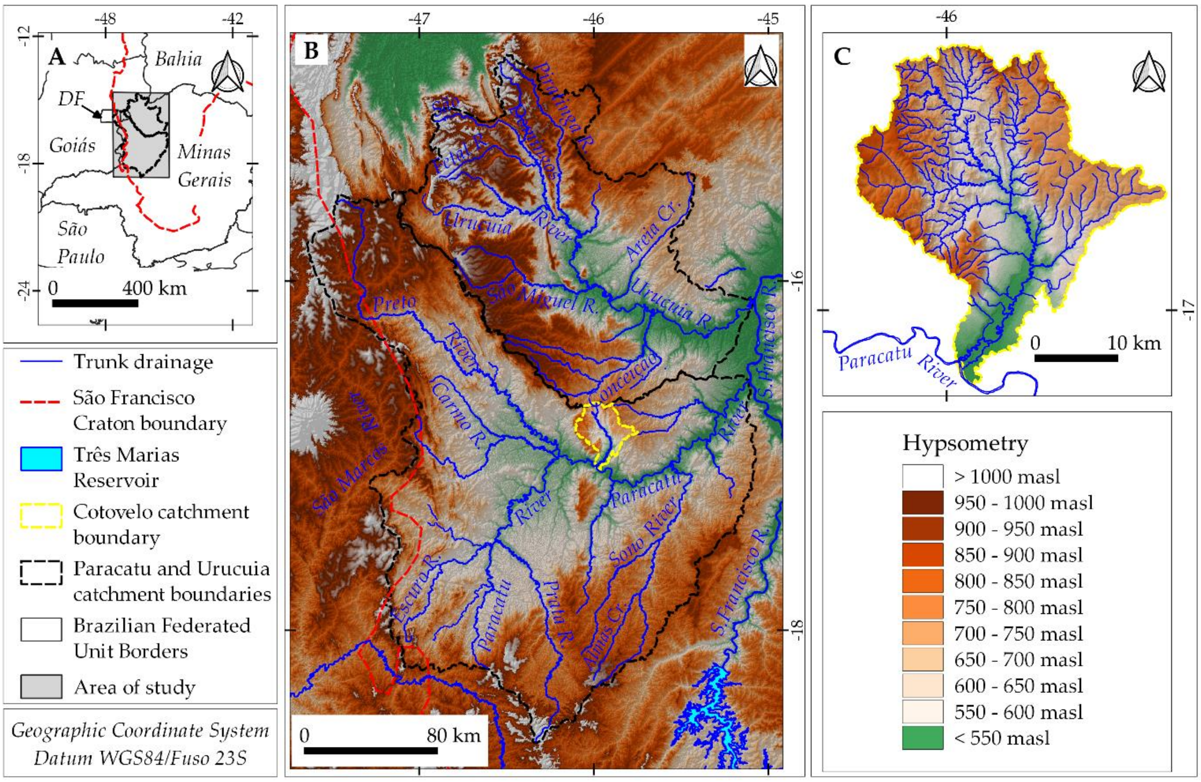

Figure 1. A) Regional emplacement of the study area related to federal unit administrative borders and the Paracatu and Urucuia catchments. The São Francisco Craton boundary is shown. B) Hypsometric map of western Minas Gerais State and adjacent areas, which host the Paracatu, Urucuia, and Cotovelo catchments, and trunk drainage region. The map was processed from the 90-m Shuttle Radar Topography Mission DEM. C) Hypsometric and hydrographical map of the Cotovelo catchment. The map was processed from the 12.5-m Advanced Land Observing Satellite-Phased Array L-band Synthetic Aperture Radar DEM. Drainage modified from the Companhia de Tecnologia da Informação do Estado de Minas Gerais (PRODEMGE) Minas Gerais State digital cartographic database.

1.2 Geological settings

The left bank tributaries of the São Francisco River and their interfluves constitute the western termination of the deformed São Francisco foreland cratonic basin (ALKMIM et al., 1993; ALKMIM; MARTINS-NETO, 2001). In contact with the Brasilia Mobile Belt (DARDENNE, 2000), both tectonic provinces are related to the Brasiliano (Upper Proterozoic) cycle (ALMEIDA, 1977; REIS et al., 2017). In the central-eastern context, the São Francisco foreland sedimentary basin represents a multiple and overlapping north–south trending cratonic coverage (ALKMIM; MARTINS-NETO, 2001, 2012), including two megasequences, the underlying Proterozoic Bambuí Group (DARDENNE, 2000; ALKMIM; MARTINS-NETO, 2012), and the overlying Phanerozoic coverages (CAMPOS; DARDENNE, 1997a; SGARBI et al., 2001). In western and northwestern Minas Gerais state, the Brasília Mobile Belt tectonic unit comprises metasedimentary megasequences of the Mesoneoproterozoic Paranoá, Canastra, Ibiá, and Vazante groups, as well as granites and associated gneisses from the Araxá group (DARDENNE, 2000; VALERIANO et al., 2004a; ALKMIM; MARTINS-NETO, 2012).

The Brasília Mobile Belt stratigraphic units (Figure 2) include the Paranoá group, a predominantly metamorphosed siliciclastic coarse-grained rock basin-fill comprising sandstones, pelitic, organic-rich shales, dolomites, and carbonate rocks (DARDENNE, 1978; 2000; ALMEIDA, 2009; DIAS, 2011; CAMPOS et al., 2013; REIS et al., 2017). The Canastra group encompasses an association of psammitic and pelitic metasediments, frequently containing carbonate and mainly consists of phyllite and imbricated quartzite lenses metamorphosed in the greenschist facies, as well as turbiditic intercalations of quartzites (VALERIANO et al., 2004a; ALMEIDA, 2009; RODRIGUES et al., 2010; DIAS, 2011; CAMPOS et al., 2013; CARVALHO et al., 2019). The Araxá group consists of intensely deformed volcanosedimentary to metasedimentary and metamorphic sequences as well as dominant igneous mafic and ultramafic rocks covered by detrital micaceous micaschist and quartzite (DARDENNE, 2000; SEER et al., 2001; DIAS, 2011; SEER; MORAES, 2013; PIMENTEL, 2016; VALERIANO et al., 2004b). The Vazante group is a basin-fill metasedimentary unit composed of interlayered marine carbonates and pelitic-dolomitic sequences with phyllite, shales, quartzites, conglomerates, and basal diamictites (DARDENNE, 2000; PIMENTEL et al., 2011; RODRIGUES et al., 2012; ALKMIM; MARTINS-NETO, 2012).

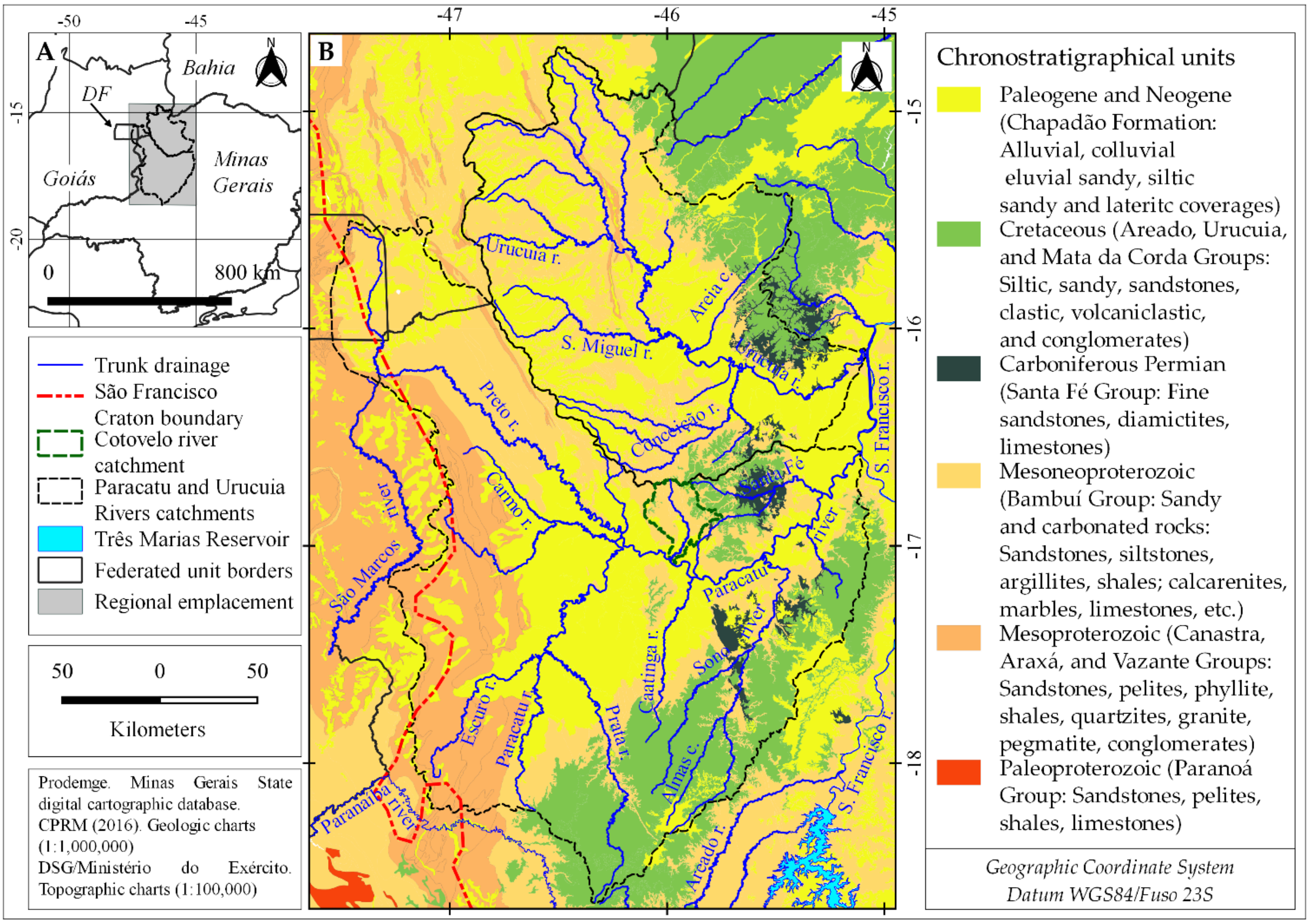

Figure 2. Geologic setting. A) Regional emplacement. B) Simplified stratigraphy of the western São Francisco Craton and eastern Brasília Mobile Belt in northwestern Minas Gerais State and adjacent areas. Geology modified from Schobbenhaus et al. (1985) and drainage modified from the PRODEMGE Minas Gerais State digital cartographic database.

The Bambuí group is an Ediacaran foreland basin covering the São Francisco Craton (REIS et al., 2017). It contains a succession of siliciclastic and carbonated shallow-marine sediments and metasediments including pelites, siltstones, shales, argillites, sandstones, limestones, marls, dolomites, calcarenites, and basal conglomerates (DARDENNE, 1978; REIS et al., 2017). Six formations have been described in this group: Sete Lagoas, Serra de Santa Helena, Lagoa Formosa, Lagoa do Jacaré, Serra da Saudade, and Três Marias (COSTA; BRANCO, 1961; DARDENNE, 1978; FRAGOSO et al., 2011). At the centre of the undeformed cover, these formations have nearly flat-layered and less deformed sectors; on the western edge of the basin, adjacent to the craton-mobile belt tectonic boundary, emergent reverse faults and thrusts-and-fold terrains of the metamorphic belts affect nearby rocks (ALMEIDA, 1977; ALKMIM; MARTINS-NETO, 2001, 2012; REIS; ALKMIM, 2015). Four structurally deformed Bambuí formations (Sete Lagoas, Lagoa do Jacaré, Serra de Santa Helena, and Serra da Saudade) were integrated into the Paraopeba subgroup (SCHOBBENHAUS et al., 1985). The Três Marias formation is the highest and most recent unit, predominantly brown and brownish medium to fine arcosean sandstones as well as light-grey arcosean siltstones, green slate, shales, and light-grey limestones, which overlie all other formations, extensively outcrops and closes the sedimentary megasequence (DARDENNE, 1978; LIMA et al., 2007; UHLEIN et al., 2011).

Over the cratonic Proterozoic successions, the Sanfranciscan Basin, a Phanerozoic sedimentary sequence, lies unconformably and presents a thickness of hundreds of meters that was built up by various mineralogical and lithological compositions and provenances. This sequence is piled up in a thicker clastic with sandy and siltic-sandy coverage, which encompasses the Carboniferous-Permian glaciogenic deposits of the Santa Fé group, Middle to Upper Cretaceous continental deposits of Areado group, Upper Cretaceous volcanic, volcaniclastic, and sedimentary rocks of the Mata da Corda and Urucuia groups, and Upper Cenozoic unconsolidated alluvial and colluvial sediments of the Chapadão formation (CAMPOS; DARDENNE, 1997a, 1997b; SGARBI et al., 2001; REIS; ALKMIM, 2015; REIS et al., 2017).

1.3 Tectonic settings

Three main macroscale features define the regional tectonic scenario: Pirapora Aulacogen, Brasilia Mobile Belt, and São Francisco Craton. The Pirapora Aulacogen is a complex system of "NW-SE striking normal faults and conjugate NE-oriented structure" (REIS et al., 2017), derived from a Lower Proterozoic rift structure that traverses the São Francisco Craton, extending up between two structural highs, the Sete Lagoas to the South, and the Januária to the North (ALKMIM; MARTINS-NETO, 2001; REIS; ALKMIM, 2015).

The Brasilia Mobile Belt and São Francisco Craton provinces share a tectonic contact roughly west of the South-North Araxá-Vazante-Paracatu-Unaí alignment (ALMEIDA, 1977). The western sub-setting is an imbricated passive margin domain (ALKMIM, 2004; PIMENTEL, 2016) characterised by a complex polyphase thrust-and-fold belt, west-dipping thrusts and folds, and inverse as well as strike-slip faults, comprising a series of nappes, such as Araxá, Passos, and Luminárias (VALERIANO et al., 2000) assigned to the West-East tectonic transport of the Brasília Mobile Belt and positioned near and on the cratons (PIMENTEL, 2016). This tectonic background (Figure 3) was inherited from the Brasiliano Orogeny, which led to the inversion of the Mesoproterozoic and Neoproterozoic passive-margin sedimentary basins surrounding the São Francisco Craton (SCHOBBENHAUS et al., 1985; HASUI; HARALYI, 1991; ALKMIM et al., 1993; CAMPOS; DARDENNE, 1997b; UHLEIN et al., 2012; PIMENTEL, 2016). Generally, NW-SE to NNW–SSE reverse and left-lateral strike-slip Precambrian fault patterns characterize the central part of the Brasília Mobile Belt (ALKMIM; MARSHAK, 1998; VALERIANO et al., 2000) forming thrust-and-fold structures, dipping thrusts, and nappes. Such structural style is evocative of a compressional regime, derived from regional-scale compressive tectonic settings: ductile and brittle shear zones, partially obliterated (VALERIANO et al., 2000; REIS; ALKMIM, 2015) with a 20–150 km broad older structure. The Brasília Mobile Belt extends for approximately 800 km, in a roughly south-north direction, from the Southern Minas Gerais to the Eastern Tocantins States.

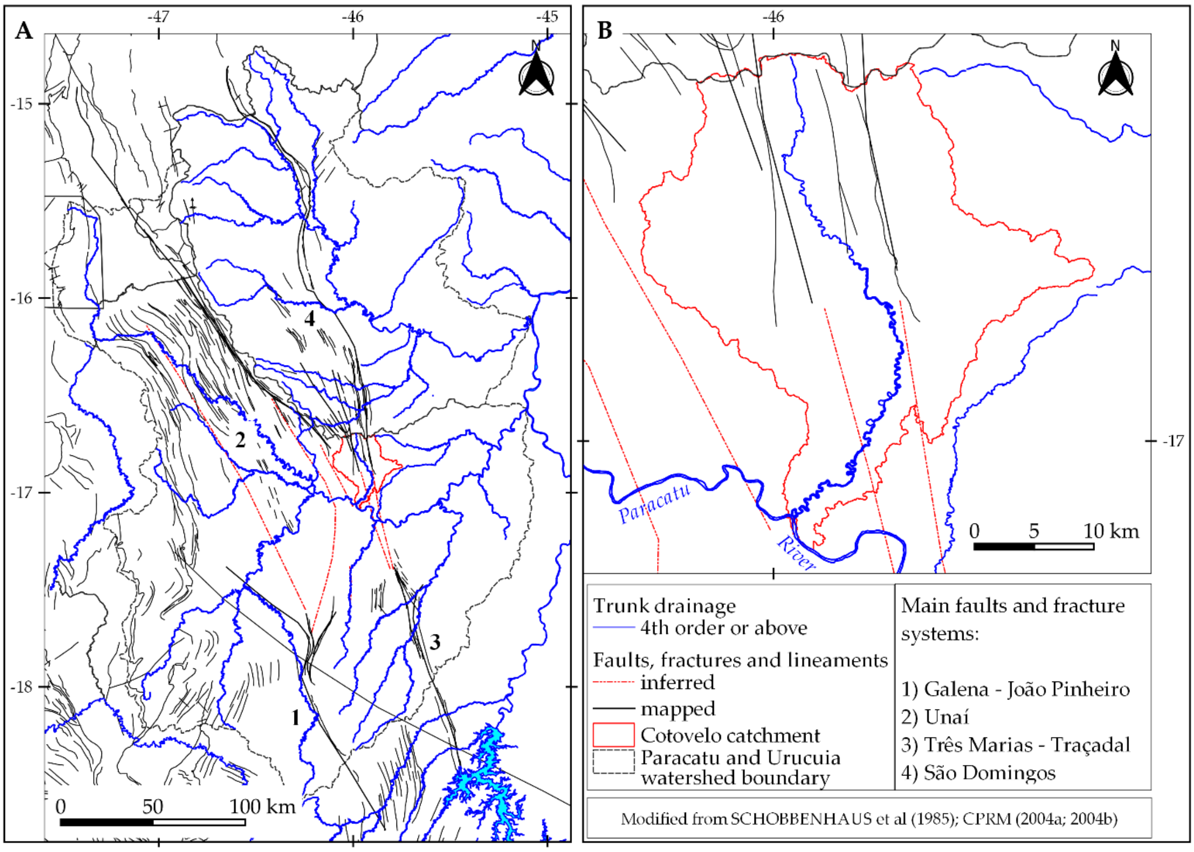

Figure 3. Tectonic setting. A) Main regional Precambrian and Phanerozoic faults and lineaments in the contact between the Brasília Mobile Belt and São Francisco Craton. B) Enlarged Cotovelo River catchment showing the mapped regional faults and lineaments. Compiled and modified from SCHOBBENHAUS et al. (1985) and CPRM (2004a; b).

The eastern sub-setting corresponds to the adjacent foreland basin deposited in the context of a shallow marine environment over the Palaeocontinent São Francisco at the end of a Wilson cycle (CHANG et al., 1987; ALKMIM; MARSHAK, 1998) during the Proterozoic, and closed at the end of the Upper Proterozoic Brasiliano Orogenic cycle. Contemporary, coverage wedges were tectonically emplaced in the cratonic domain (ALMEIDA, 1977; PEDROSA-SOARES et al., 1994; DARDENNE, 2000; PIMENTEL et al., 2000).

In western Minas Gerais, the Bambuí group displays an approximately N-S undeformed, sub-horizontal Proterozoic coverage of the central part of the cratonic basin (ALKMIM et al. 1993; VALERIANO et al. 1995; VALERIANO et al., 2000; REIS; ALKMIM, 2015). However, a post-Palaeozoic extensional tectonic event, related to the break-up of western Gondwana (HASUI, 1990; ALKMIM; MARTINS-NETO, 2001) has been shown to affect these rock strata, developing extensional normal fault systems (BARCELOS; SUGUIO, 1980), reactivating Neoproterozoic discontinuities, and creating a series of half-grabens (SAWASATO, 1995; FRAGOSO et al., 2011), which, for example, partially controlled the Areado group sedimentation (BARCELOS; SUGUIO, 1980; HASUI; HARALYI, 1991; FRAGOSO et al., 2011). Due to Middle Phanerozoic tectonics, the Lagoa do Jacaré formation was emplaced on the Três Marias formation by the NW-SE Galena west-dipping reverse fault, referred in the Presidente Olegário geologic chart (KATTAH, 1991; FRAGOSO et al., 2011). In this context, the remarkable cratonic tectonic feature is the alignment of two NNW-SSE parallel fault systems correlated with the Paraopeba subgroup (SCHOBBENHAUS et al., 1985) and matching the Precambrian shear zone (CPRM/COMIG, 2003a; 2003b).

During the Cretaceous reactivation (SGARBI, et al., 2001), the Alto Paranaíba uplifting (HASUI et al., 1975; HASUI; HARALYI, 1991) controlled the NW-trending alkaline magmatism in the southwestern part of the Sanfranciscan Basin (HASUI et al., 1975; BARCELOS; SUGUIO, 1980; HASUI; HARALYI, 1991; SGARBI et al., 2001), which piled up in correlative grabens (CAMPOS; DARDENNE, 1997b). Initially, isostatic rebound followed by uplift and tectonic reactivation of sub-meridian-oriented faults (SGARBI et al., 2001), a feature that also explains the separation between the Paraná River catchment, SSW, and the São Francisco River catchment to the NNE

(HASUI; HARALYI, 1991). It also led to the synchronous Mata da Corda volcanic and sedimentary episodes, as well as clastic sedimentation in the context of the Abaeté Depression (HASUI; HARALYI, 1991; ALKMIM; MARTINS-NETO, 2001), an extensional NNE-SSW-trending system influenced by the Mata da Corda Flexure (HASUI et al., 1975; HASUI; HARALYI, 1991). Finally, a Middle to Upper Cenozoic brittle tectonic NE-trending cycle, resulting from the reactivation of previous Precambrian and Cretaceous weakness zones, has been shown to control the low drainage density over sandstones and exert a strong influence over the rectangular drainage pattern (CAMPOS; DARDENNE, 1997b). Being the newest regional mapped tectonic features, these normal NE-trending faults and those NNW-trending strike-slip as well as reverse faults outline the present regional drainage directions and patterns (ALKMIM; MARTINS-NETO, 2001).

1.4 Geomorphological settings

The Brazilian Shield has been described as a conspicuous broad plateau-like erosive feature (Figure 4) including, in the study area, three geomorphological units (CETEC, 1981; 1983): The *Planaltos do São Francisco* (São Francisco Plateau), *Depressão do São Francisco* (São Francisco depression), and *Cristas de Unaí* (Unaí Crests). Regionally, the *Planaltos do São Francisco* geomorphic unit acquired different toponyms, such as the *Geral do Rio Preto, Santa Teresa, Santa Fé, Boqueirão, Maravilha*, and *Mata da Corda* plateaus and *Gerais* tableland. Similarly, the smaller sectors of the *Depressão do São Francisco* were locally titled by the names of rivers that drain them.

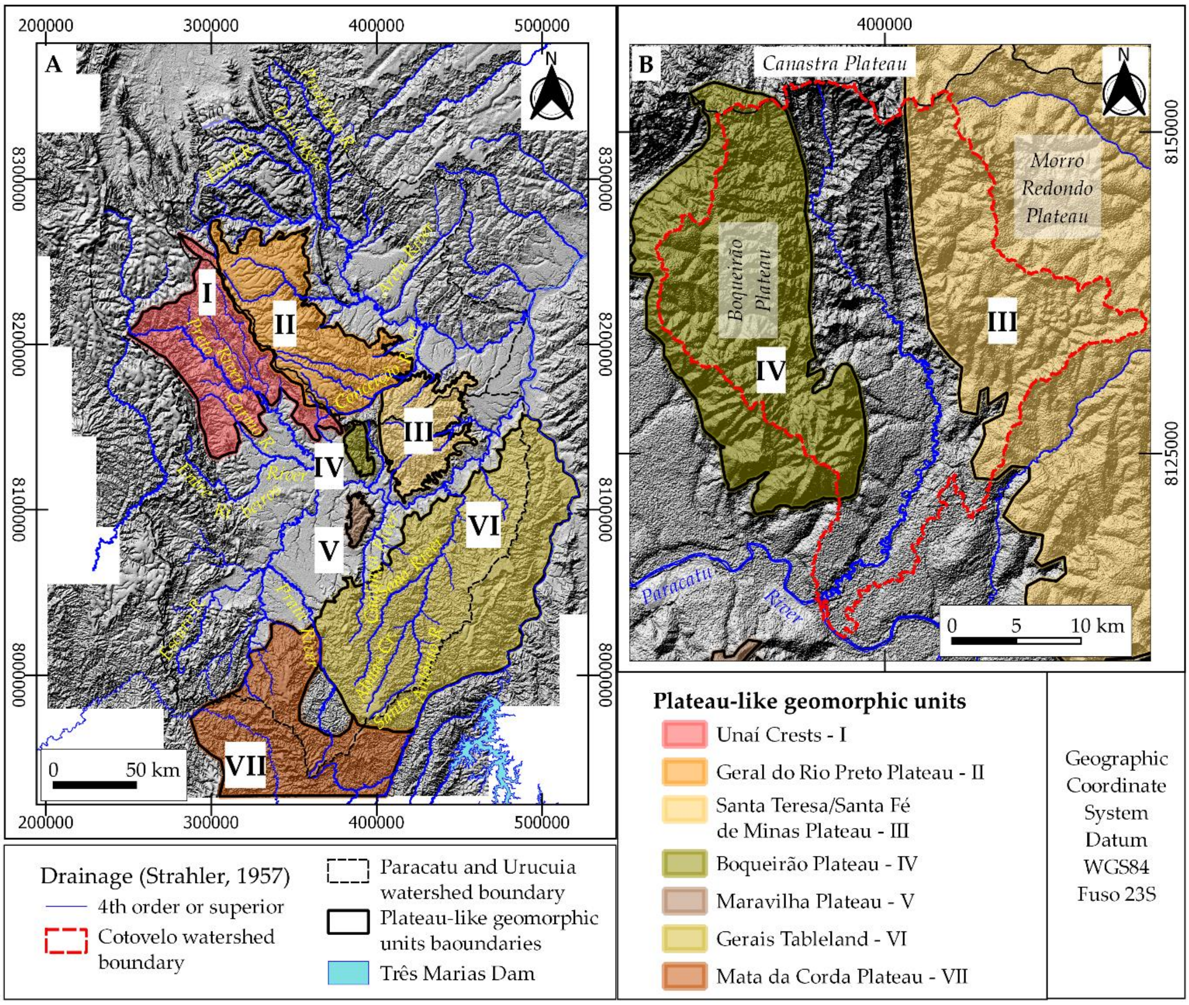

Figure 4. Geomorphic setting. A) Main regional plateau-like features within the Paracatu and Urucuia watershed boundaries and representatives of the Planaltos do São Francisco regional geomorphic unit. B) Plateau-like features at the Cotovelo watershed boundary.

The São Francisco Plateau is characterised by broad and extensive sandy-sedimentary-covered interfluves, locally lateritic, delimited by erosive vertical scarps, and tableland morphology. That morphogenesis was correlated with climatic weathering and fluvial erosion of the Cretaceous sandstones. Three internal sub-units divide the São Francisco Plateau (CETEC, 1981; 1983). The *Superfície tabular* (Horizontal obliterated surface), which is a planation surface (800–1,000 masl) built over Cretaceous rock groups Areado and Mata da Corda and Urucuia (where it is delimited by vertical scarps, it is called “chapada” landform). The *Chapadão dos Gerais* (Gerais Tableland), an extensive regional geomorphic feature in the southern Paracatu watershed boundary, the *Serra do Boqueirão* (Boqueirão Plateau) and the *Serra Geral do Rio Preto* (Geral do Rio Preto Plateau), which portray the Paracatu-Urucuia catchments divide as well as the *Planalto da Mata da Corda* (Mata da Corda Plateau) in the southwestern Paracatu River catchment, delineate the landform unit.

The *Superfície tabular reelaborada* (horizontal obliterated reworked surface) is a stepped landform (600 and 800 masl) corresponding to the left margin drainage divide of the São Francisco River catchment, is covered by weathered sandy and sandstones from the Cretaceous Três Barras formation (Areado group) and by volcaniclastic sandy and sandstone from the Capacete and Patos formations (Mata da Corda group). Where this cover was eroded, and the surface lies over the Precambrian Bambuí group rocks. The *Serra de Santa Teresa* (Santa Teresa Plateau), *Planalto de Santa Fé de Minas* (Santa Fé de Minas Tableland), and eastern slopes of the *Serra da Maravilha* (Maravilha Plateau) exemplify the geomorphic unit.

Ultimately, the *Superfície tabular ondulada* (undulated obliterated reworked surface), steepest escarpment border, and steep slope surface analogous to the previous one can be differentiated based of the exposition of clayey rock strata from the Cretaceous Quiricó formation (Areado group) and the complex lithology of the eastern Brasília Mobile Belt. Numerous residual landforms within the Paracatu and Urucuia catchments, situated in the transition between previous geomorphic units and the present floodplain, both within the São Francisco depression, represent the surface.

The São Francisco depression consists of a broad, lowered, undulated, pediplanated, sedimentary area and inter-plateau escarpments along the São Francisco catchment tributary rivers and their floodplains, approximately 500 masl, essentially composed of remobilized sedimentary units of the Chapadão formation.

The Unaí Crests designate an aligned set of ridges elaborated over the psammitic-pelitic-carbonated sequence of the Paranoá group and Paraopeba subgroup (SCHOBBENHAUS et al., 1985; CAMPOS et al., 2013). They rise prominently above the surrounding entrenched and NW-SE structurally oriented valleys, generally exhibiting hilly landforms with scarps or steep slopes and narrow summits. The Preto River, a major left-bank tributary of the Paracatu catchment, drains this unit.

2. Methods

Based on the morphotectonic method, this research used lineament mapping to assess the regional geomorphology and the river network, searching for landforms with direct or indirect evidence of tectonic activity or reactivation in intraplate environments. Here, the term lineament refers to long linear or curvilinear natural features mostly controlled by structure or lithology (O’LEARY et al., 1976). Currently, there are several approaches to interpret geomorphological aspects in medium-to-high spatial resolution images and digital elevation models (DEM), which contribute to better identification and mapping of structural lineaments (CLARK; WILSON, 1994; MOSTAFA; ZAKIR, 1996; PARANHOS FILHO et al., 2013; HERMI et al., 2017). This research used independent and associated remote sensing products to map crustal lineaments using manual methods.

Sequential reasoning for lineament extraction and analysis obeyed the following adapted method (HUNG et al., 2005; THANNOUN, 2013; DAS et al., 2018) in five successive steps:

a) Selection of suitable satellite image bands and DEM resolution.

b) Enhancement of image and DEM lineament directional patterns based on filters such as Laplacian and Sobel (CHUVIECO, 1996).

c) Visual identification of lineaments, and manual draw as well as mapping with Quantum GIS 3.14 (QGIS Development Team, 2021) drawing tools.

d) Evaluation of the resultant lineament map, in vector format, with respect to the literature information.

e) Evaluation and description of river pattern and supposed tectonic setting with respect to the mapped information.

2.1 Data set selection

Two remote sensing products were handled: satellite images and DEM; one scene of the Operational Land Imager (OLI)/Landsat-8, with a spatial resolution of 30 m per pixel, with the chosen bands ranging from shortwave, panchromatic, blue, green, red, and near-infrared (0.450–0.885 μm) spectral resolution. Three different terrain models were used: the Shuttle Radar Topography Mission DEM (SRTM DEM) that has a spatial resolution of 3 arc second or 90 m, (LP-DAAC, 2018a); the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM) with a spatial resolution of 30 m (LP-DAAC, 2018b); and the Advanced Land Observing Satellite-Phased Array L-band Synthetic Aperture Radar DEM (ALOS-PALSAR DEM), with a spatial resolution of 12.5 m (ASF-DAAC, 2015). DEMs with different spatial resolutions were chosen due to the complex geotectonic environment, which refers to the contact between two structural provinces, and used in a complimentary way. Medium-scale products, such as the 90-m DEM, provide data at a regional extent that are correlated to this terrain, thus leading to the mapping of their related features. Low-resolution products, such as the 12.5- and 30-m DEMs, support the identification and mapping of small-scale features that are not under regional structural control.

Moreover, a processed cartographic lineament database of the Mesozoic sedimentary Abaeté sub-basin map (HASUI; HARALYI, 1991) was digitised, compiled, and incorporated to improve the vector database density and accuracy. High spatial resolution images from the Google Earth™ Platform provided support to unscramble and redraw detailed features. Furthermore, structural data were digitised by hand over scanned topographic map sheets at a scale of 1:100,000: Bocaina (DSG/ME, 1969a), Bonfinópolis de Minas (DSG/ME, 1970), Canabrava (DSG/MG, 1969b), and Serra do Boqueirão (DSG/ME, 1969c). Another set of structural data was obtained using the same method over two geologic map charts, at a scale of 1:250,000: João Pinheiro (CPRM/COMIG, 2003a) and São Romão (CPRM/COMIG, 2003b).

2.2 Image and DEM processing

The multispectral and panchromatic bands were previously subjected to atmospheric correction and filtering for enhancement (CHUVIECO 1996). Different RGB colour compositions were generated, and R1G3B5 and R4G5B7 provided the best feature visualisation. Five-step digital convolution procedures were applied to the infrared satellite band data (MOORE; WALTZ, 1983; SUZEN; TOPRAK, 1998) to i) generate a low-frequency image; ii) generate directional components over the image by increasing the contrast of edge and line segments, which was performed by applying a median filter (3 × 3) to all Landsat-8/OLI bands for radiometric correction and atmospheric noise removal (SUZEN; TOPRAK, 1998); iii) smooth the image and reduce secondary processing effects; iv) manually extract lineaments of the smoothed image; and v) add the extracted lineaments to the original image and re-scale to an 8-bit domain (256 greyscale) for display. This method was modified by introducing north-, south-, east-, west-, northeast-, and northwest-oriented Laplacian and Sobel directional filtering (CHUVIECO, 1996), which was applied to the resulting image, with a solar zenith of 45° and azimuth angles of 45°, 135°, and 225°. The resulting images were merged to obtain different RGB colour compositions for visual inspection.

The multi-scale DEM was processed using shading and 3D models, and reflectance corrections, thus producing slope, aspect, hill-shades, and hypsometric maps (KARNIELI et al., 1996; LIU, 2003; MANTELLI; ROSSETTI, 2009; MELO; ROSSETTI, 2015) by using Zevenbergen and Thorne's (1987) algorithm, which is available from QGIS. These intermediate products were generated with respect to four preferential azimuth values (45°, 135°, 225°, and 315°) perpendicular to the main regional structural directions referred to in the literature. Vertical exaggeration of z-values at 10× and 25× and a solar zenith of 45° enhanced the linear feature visualisation, in correlation with topographic depressions, and emphasised subtle changes on the terrain surface (MOORE; WALTZ, 1983; MAH et al., 1995; ANDRADES FILHO; ROSSETTI, 2012). The resulting maps were suitable for underlying the vector database of lineaments and other natural features at the regional scale. The same procedure was applied to an ALOS-PALSAR DEM scene, which provided the Cotovelo catchment-scale information.

2.3 Visual lineament identification and mapping

Enlarging the third step of the previously described digital convolution technique, differential texture, hue, roughness, and structures over the processed images and DEM supported the visual interactive identification of lineaments. Sequentially, multiple images and DEM colour composites provided support to draw lineaments (SARTORATO, 1998; KOÇAL, 2004) on screen using the QGIS digitising tools (QGIS Development Team, 2021).

Based on visual inspection, all features that seemed to be a positive or negative lineament were mapped indistinctly. Initially, scale and size were not considered because the main objective was to densify the available lineament database. Subsequently, the new vector database was converted to the WGS84 geo-reference system using Envi 4.7 and QGIS 3.14. Finally, the resulting map was fitted to the UTM-WGS84 projection and coordinate systems, namely, zone 23S, and then superimposed on the drainage network extracted from the topographic maps at 1:100,000 to perform a visual inspection of the regional approach.

2.4 *Quantitative and spatial treatment of the lineaments*

The new lineament database was entered into a vector-based geographic information system shapefile format layer and subjected to geometric and quantitative analyses, encompassing histograms of azimuth, length, frequency (MOSTAFA; ZAKIR, 1996), polar diagrams (KARNIELI et al., 1996), and density maps (ARLEGUI; SORIANO, 1998; ZAKIR et al., 1999; HUNG et al., 2005; THANNOUN, 2013). This information provided a general and sectoral overview of the structural setting of the study area. Vectors were pre-processed using QGIS to calculate the length, azimuth, and frequency. The resulting data were integrated into Stereo 32 (RÖLLER; TREPMANN, 2003).

Lineament density maps include concentrated or dispersed values in number or length per unit area (m/m², km/km², number/km²), with higher values associated with the main structures (ARLEGUI; SORIANO, 1998; HUNG et al., 2005). Density analysis was performed in QGIS by applying the *Line density* function to the full line vector layer, which preserved the length and azimuth attributes. These vertices were then subjected to an interpolation process to create Thiessen polygons and generate their centroids with the length data of the original line. Finally, a density map layer in raster format with a 90 m spatial resolution was built using inverse distance weighted (IDW) interpolation (BURROUGH, 1986). After the interpolation process, contour-like lines were generated, thus creating discrete classes of fractured zones, and lineament density values were assessed and established in three density categories: low, intermediate, and high.

As described by Aronoff (1989), a finite ordered set of connected points define a line feature and individual lineaments were drawn as lines. Their individual lengths were calculated in QGIS, and the results were plotted against the main observed regional structural directions (THANNOUN, 2013).

2.5 *Drainage pattern analysis*

The river network was assessed and different patterns were delimited at regional Paracatu and Urucuia River catchments by means of visual inspection of medium-resolution satellite images and topographic charts at a scale of 1:100,000, as well as within the Cotovelo River catchment, using shaded relief and hypsometric maps processed from the high-resolution ALOS-PALSAR DEM. For both steps, the assessment aimed to identify possible drainage patterns (ZERNITZ, 1932; HOWARD, 1967).

3. Results and discussion

Preliminary spatial information derived from remote sensing products was converted into a vector GIS layer with cartographic attributes encompassing 1,721 vectors representing natural linear features (O’LEARY et al., 1976) correlated to crustal lineaments, which resulted in a new, denser map of regional lineaments (Figure 5). Drawn mapped lineament totalled 20,797 km in length, which corresponds to 192.6 m/km² (or 0.19 km/km²). These features were combined into a single shapefile layer and supported the overlay and integration of a hydrographic database, while the composed layer became a useful base for investigating the regional and local drainage patterns.

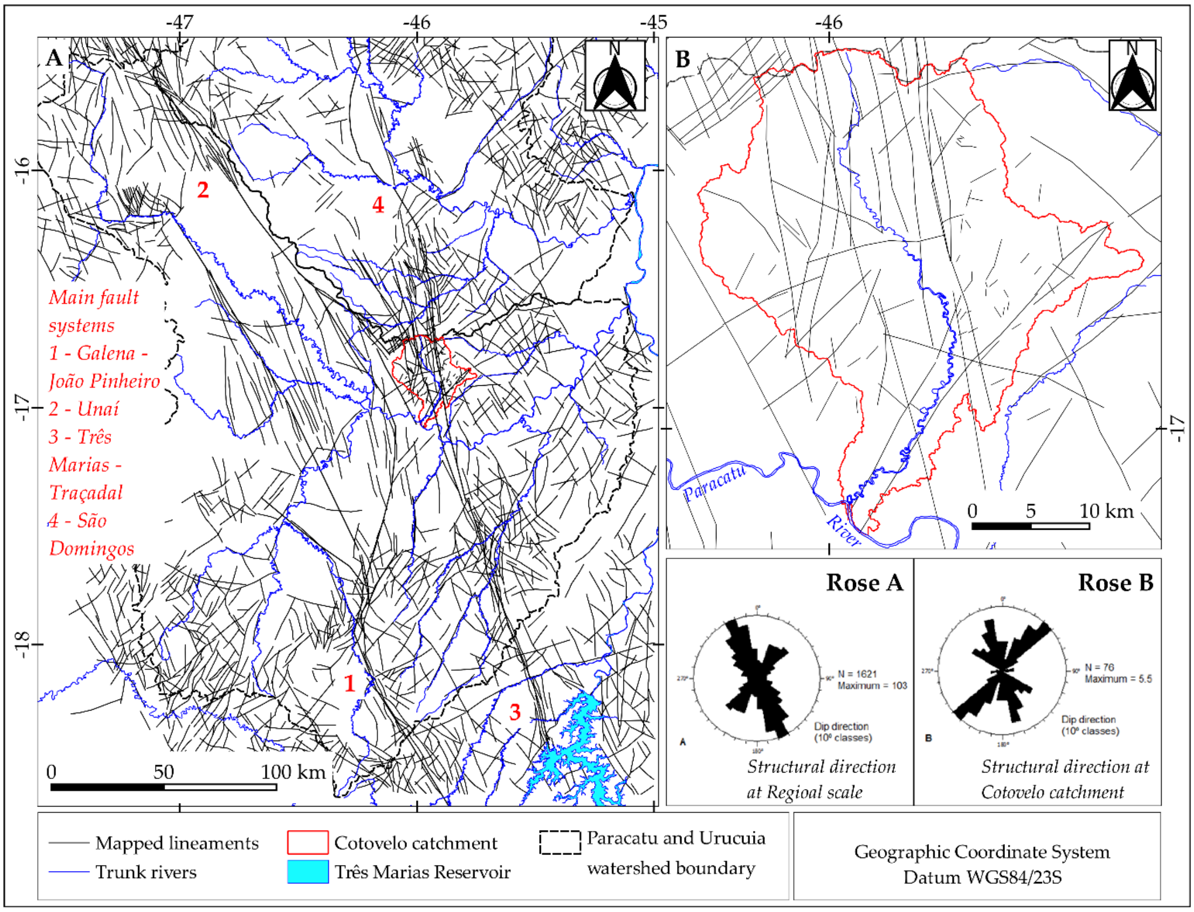

Figure 5. Currently mapped lineaments. A) New mapping of lineaments in the western São Francisco Craton and Eastern Brasília Mobile Belt. B) New detailed mapping of lineaments in the Cotovelo River catchment and adjacent areas. Rose A: Polar histogram indicating the predominant regional structural direction from the mapped lineaments. Rose B: Polar histogram showing local structural directions within the Cotovelo River catchment.

Two main regional structural directions were identified. The first was a NNW-SSE (N320-350E) system, corresponding to the contact of the Brasília Mobile Belt and the São Francisco Craton (Rose A). This system was better recognised over the oldest cratonic basement and inside the Tocantins Province, the structural province under the Brasilia Mobile Belt (REIS et al. 2017). The second was an SW-NE (N20-40E) system, well-constrained over the Precambrian and Cretaceous rocks, corresponds to the Mesozoic-Cenozoic tectonic events.

Within the Cotovelo catchment, a directional analysis was performed with 76 lineament vectors (Rose B) and two main directions were identified. First, SW-NE (N30–50E), correlated to Mesozoic-Cenozoic tectonic events was recorded in the Precambrian and Mesozoic rocks. Second, NNW-SSE (330–350E), corresponding to Precambrian basement rock structures, was evident of the Bambuí group. Therefore, the structural directions inside the catchment reproduced the regional directions.

Lineament density analysis encompassed concentrated or dispersed values (km/km²) across the entire study area (Figure 6).

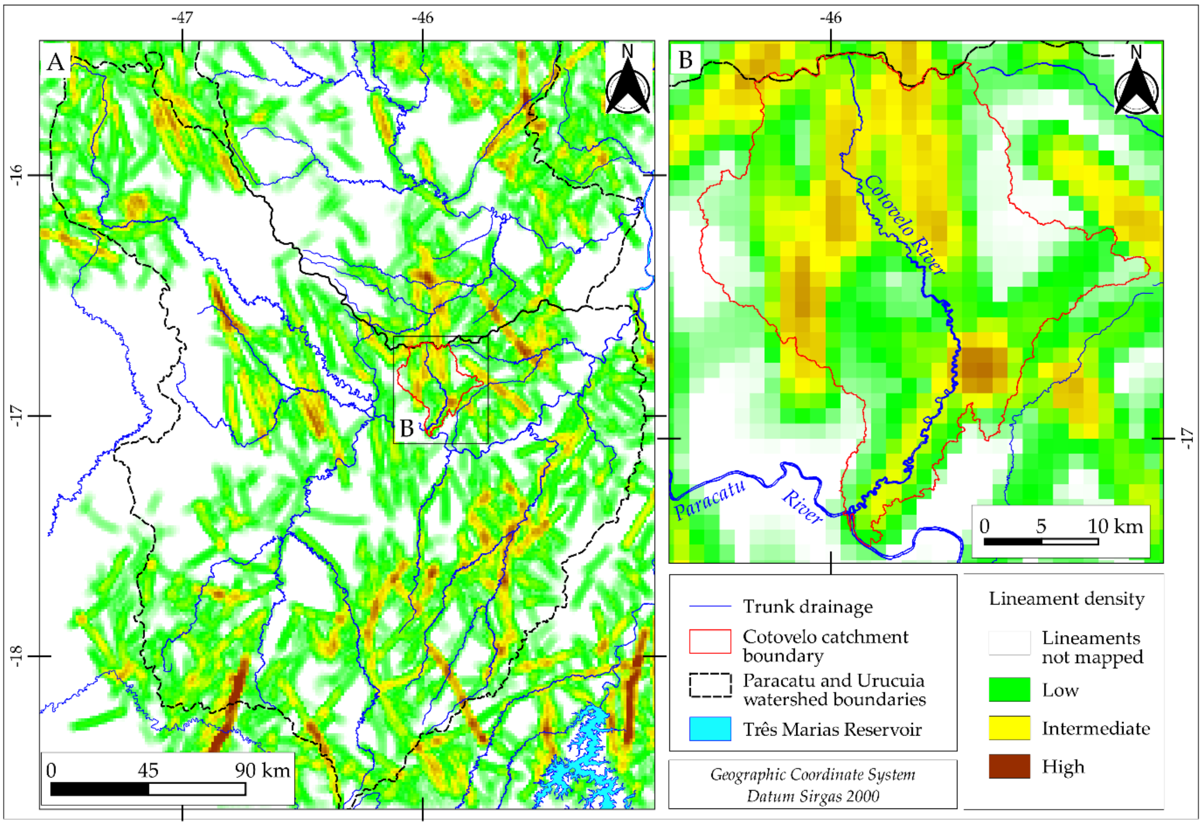

Figure 6. Line density map quantifying the relative spatial distribution of lineaments. A) Regional lineament density setting. Higher density areas correlate with rock outcroppings as well as with higher regional altitudes of the São Francisco Craton. Lower-density areas spread from low slopes of intermediate altitude compartments. Both density values are common to deeply eroded areas that expose fresh and unweathered rocks. B) Cotovelo catchment lineament density setting. Higher-density areas are concentrated among the Paraopeba Subgroup rocks and outcropping rocks at the scarps of the Boqueirão Plateau.

First, for the entire study area, density correlated positively with altitude; that is, the highest lineament density was observed at places that were more elevated, where denudation processes expose fresh rocks; thus, facilitating lineaments identification and mapping. Second, all eastern regions presented middle- to high-density values, similar to the features observed in the northwestern Paracatu catchment, near the Preto River heads, within Unaí Crests. In the southern region, the high-density values corresponded to the Chapadão dos Gerais (Gerais Tableland), a regional flatter tableland-like landform, where the Upper Cretaceous sandstones of the Areado and Urucuia groups outcrop extensively. In the central and northern sectors, on the left bank of the Paracatu River, the highest lineament density values corresponded to the dissected landscapes of the Paraopeba subgroup at plateau scarps and lower steepest slopes.

Interestingly, the western-central Paracatu catchment and the Geral do Rio Preto Plateau exhibited low lineament density values, which can be explained by the broad and dense sedimentary regional coverage. Strikingly, the Cotovelo catchment was situated inside the densely mapped lineament zone (Figure 6B).

3.1 Drainage network arrangement

The previous structural directions inferred from lineaments contributed to the recognition and description of the regional, sub-regional, and catchment-scale structural control of the drainage network structure and pattern. These directions strictly fit into two main groups: longer rivers have their directions controlled, mostly, by NNW-SSE Precambrian structures; shorter and low-order channels adjust their flows to SW-NE and E-W Cenozoic directions (Figure 7).

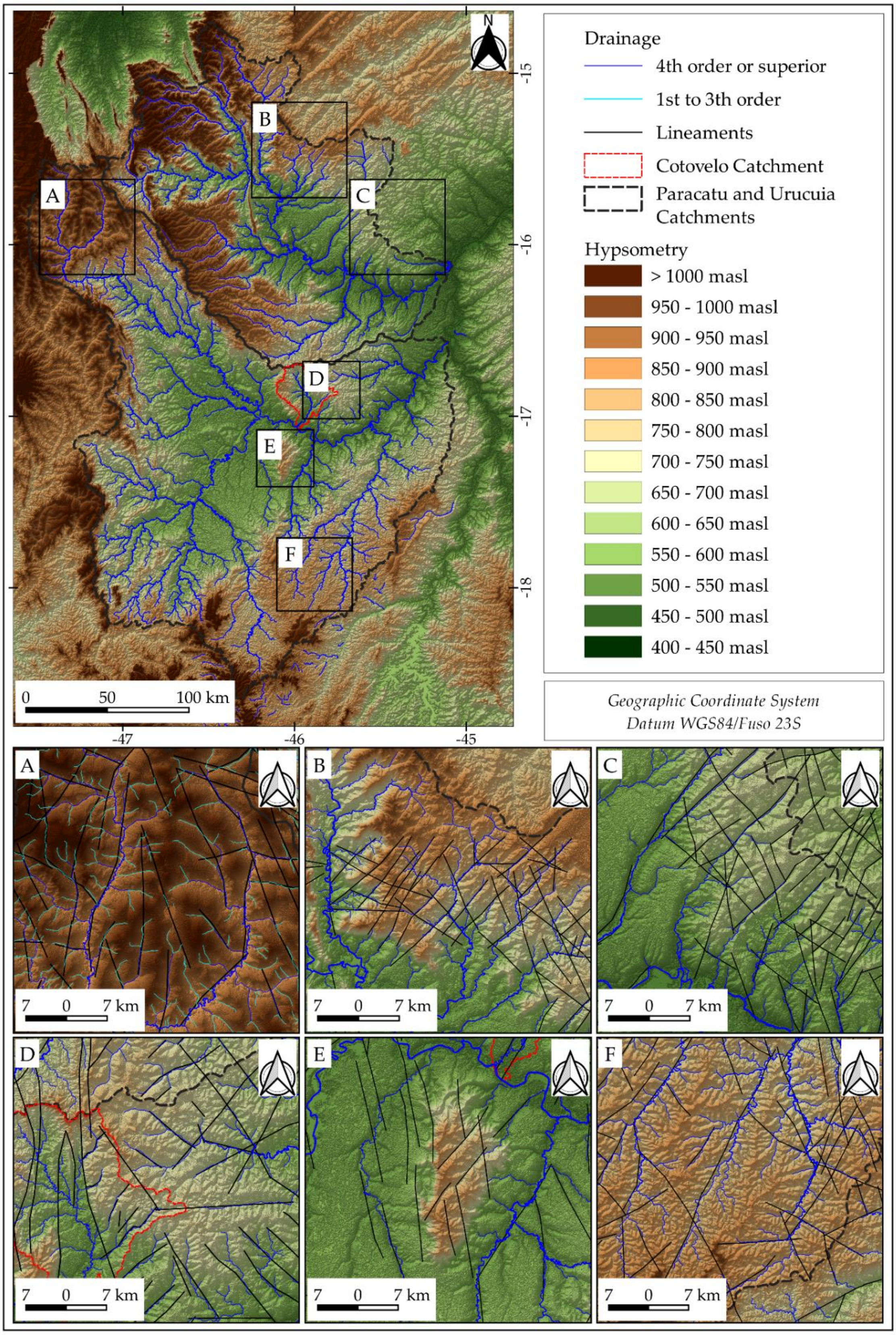

Figure 7. Drainage network overlying the hypsometric model. Boxes show close correlations between the lineaments and effective channel direction control. A) Direct correlation between NNW-SSE mapped lineament and low-order channels near the Preto River headwaters. B) SW-NE lineaments controlling low-order drainage as well as segmenting geomorphic features in the Urucuia left margin. C) SW-trending parallel drainage and first-order sub-parallel tributaries that are reoriented toward the southwest by lineaments in the Areia River catchment. D) NE-SW

oriented channels and topographic features that are directly correlated to the mapped lineaments in the Santa Teresa Plateau. E) SW-NE-oriented parallel drainage in the higher topographic levels of the Maravilha Plateau and Caatinga River channel. F) SW-NE sub-parallel-oriented dissected landscape in the Sono and Santo Antônio Rivers and Almas Creek catchments showing direct correlations with the mapped lineaments.

The regional fluvial landscape fits well with the two longest two main structural directions, NNW-SSE and SW-NE. A remarkable directional feature is due to the three distinctive segments and two abrupt directional changes characterising the Paracatu River channel. The river springs in the southwesternmost sector of its catchment and flows toward the N-NE, for 155 km, where the Prata and Escuro Rivers are its main tributaries, and their channels are partially controlled by the João Pinheiro-Galena fault system. Flowing roughly in an S-N to SSW-NNE direction, after 150 km the Paracatu River is intersected and diverted by a second course-trend, a NW-SE segment controlled by the Eastern João Pinheiro-branch Precambrian fault zone, correlated to the onlap of the mobile belt. In these 57 km-long strips, the Paracatu receives water from the Entre-Ribeiros and Preto rivers at the left margin. The Preto River, the longest tributary of the Paracatu River, is possibly a palaeotributary of the Paranaíba River catchment, beheaded by the Paracatu catchment (CHEREM et al., 2014). The Preto River springs at the ridge and valley province of Unaí Crests; after approximately 130 km-long drifting courses, the channel turns southeast and follows an almost straight course for more than 125 km until it connects to Paracatu. In total, the straight-line flow direction (Preto and Paracatu) extended for 186 km, until 15 km downstream of the Caatinga River joined Paracatu through the right margin. Moreover, 15 km downstream of the confluence of the Caatinga River, Paracatu makes another 90° turn, recovering its previous SW-NE direction, and flows until it meets the São Francisco River. In this third segment, the Sono River is the most important tributary of the catchment; a remarkable feature of the correlation between the drainage and lineaments can be observed in its catchment, where the river and its main tributaries (Santo Antônio and Alma s Rivers) definitely adjusted their channels to the SW-NE structural direction.

An analogous geometrical description fits the Urucuia River catchment area and its tributaries. However, a less evident expression of structural direction was observed for the Urucuia River channel. Urucuia and its main branches spring in the northwesternmost sector of the catchment, in the São Domingos Plateau, and flow toward the southeast. Near the springs, the Fetal, Piratinga, and São Domingos Rivers are important tributaries of the Urucuia, all for the left margin. On this path, the Urucuia River gathers the contribution of two channels, which run from W-SW toward E-NE (São Miguel and Conceição Rivers, to the right margin) and two other channels that flow from NE toward SW (Areia and Claro Rivers, to the left margin). Only 44 km before the São Francisco River, the Urucuia River makes a 90° turn, changing the flow direction to SW-NE.

Easily noticed in the topographic map (1:100,000 or more generalised scales), there is a striking collinearity among the rivers in the area: the São Francisco, the main river of the catchment, as well as Sono, Paracatu, Conceição, and Areia Rivers flow in a parallel SW-NE direction, adjusted to the Cenozoic tectonic event weaker lines (CAMPOS; DARDENNE, 1997b).

Consequently, rivers adapt to structure in two temporal-scale processes: first, in an indistinct long-term duration process, by lowering coverage and dissecting rock structures. Second, in a short-term process, by adjusting the Meso-Cenozoic weakness line direction, continuously moving due to the South American Plate cinematics. Both processes reinforce the superimposition of rivers, best perceived in the Conceição and Preto River catchments.

3.1.1 Drainage anomalies within the Cotovelo River catchment

Locally, the Cotovelo River catchment records three distinct river patterns: dendritic or sub-dendritic, orthogonal or angular/trellis, and parallel to sub-parallel, with some reaches fitting individual meandering patterns. These distinct settings show that local river networks respond to lithological and structural control (ZERNITZ, 1932; TWIDALE, 2004). Dendritic to sub-dendritic patterns correlate with erosional channels, observed in lower-order streams and spreading out of the tributary sub-catchments, because of the predominance of horizontal sedimentary rocks (HOWARD, 1967). This is the most representative pattern in the area, mostly associated with the flat-laying sandy meta-sedimentary rocks of the Bambuí group. Locally, the river network fits to lines of crustal weakness and preferential energy. Parallel to sub-parallel drainage occurs in areas of moderately steep slopes, where dissection creates short, elongated landforms (HOWARD, 1967), which drain scarps of the eastern Boqueirão and western Morro Redondo Plateau. These drainage patterns were associated with some weak zones of the Precambrian lineaments, which indicate the persistence of some fault lines acting on capturing and controlling the river path inside and near the NNW-SSE shear zone (CPRM/COMIG, 2003a; 2003b). Some peculiar sections of rivers assessed individually revealed interesting and conspicuous drainage anomalies characterised by straight reaches connected in angular junctions (Figure 8), which point to orthogonal or angular patterns (TWIDALE, 2004). These sections were identified in valleys crossing the densely folded and fractured pelitic rocks of the Serra da Saudade and Lagoa do Jacaré formations and correlate to the plunges of the folded (anticline and syncline) structures, particularly inside the NNW-SSE shear zone. Furthermore, numerous confluences enter the higher-order streams at approximately 90° (Figure 9). Small streams were strictly adjusted to weaker lines on the flanks of the fractured anticlines with local trunk rivers flowing along the axis of the synclines (Figure 10 and Figure 11).

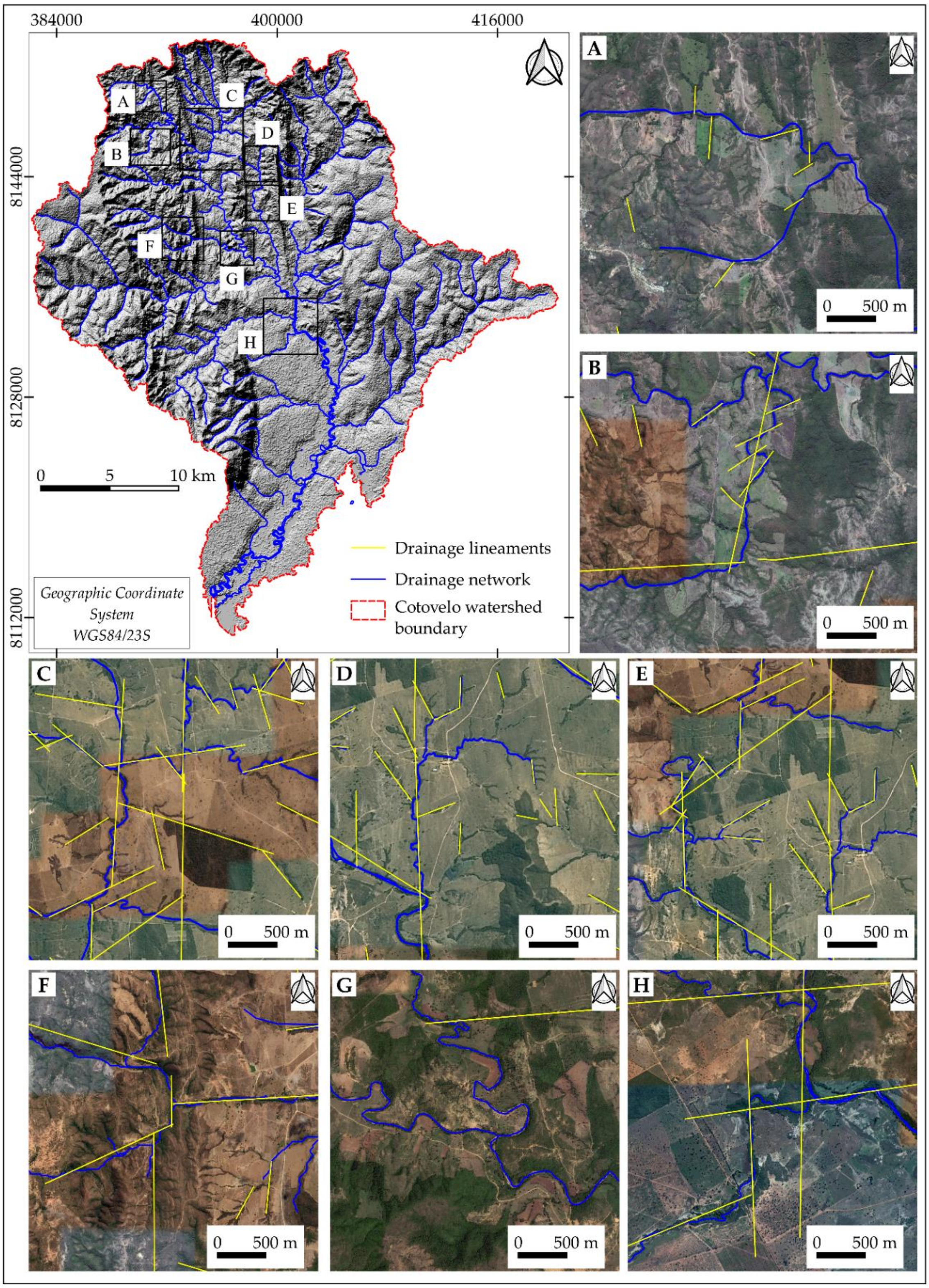

Figure 8. Detailed mapped lineament at the Cotovelo catchment scale, and correlated channel anomalous deflections plotted on a Google Earth satellite image. A) Angular junction and deflection at the Capivara Creek catchment. B) Drainage deflection at a right angle (almost 90º) in the tributary of the Capivara Creek. C) Angular junctions and deflected drainage in the Cotovelo River channel. D and E) High-angle angular junctions and deflected drainage in the Terra Vermelha Creek channel. F) Deflected drainage at the Alegre Creek channel. G) Anomalous entrenched segment in the Cotovelo River channel and its right bank tributary, the Alegre Creek. H) Abruptly deflected channel of the Trombas Creek, a right bank tributary of the Cotovelo River. Modified from Google Earth (2021).

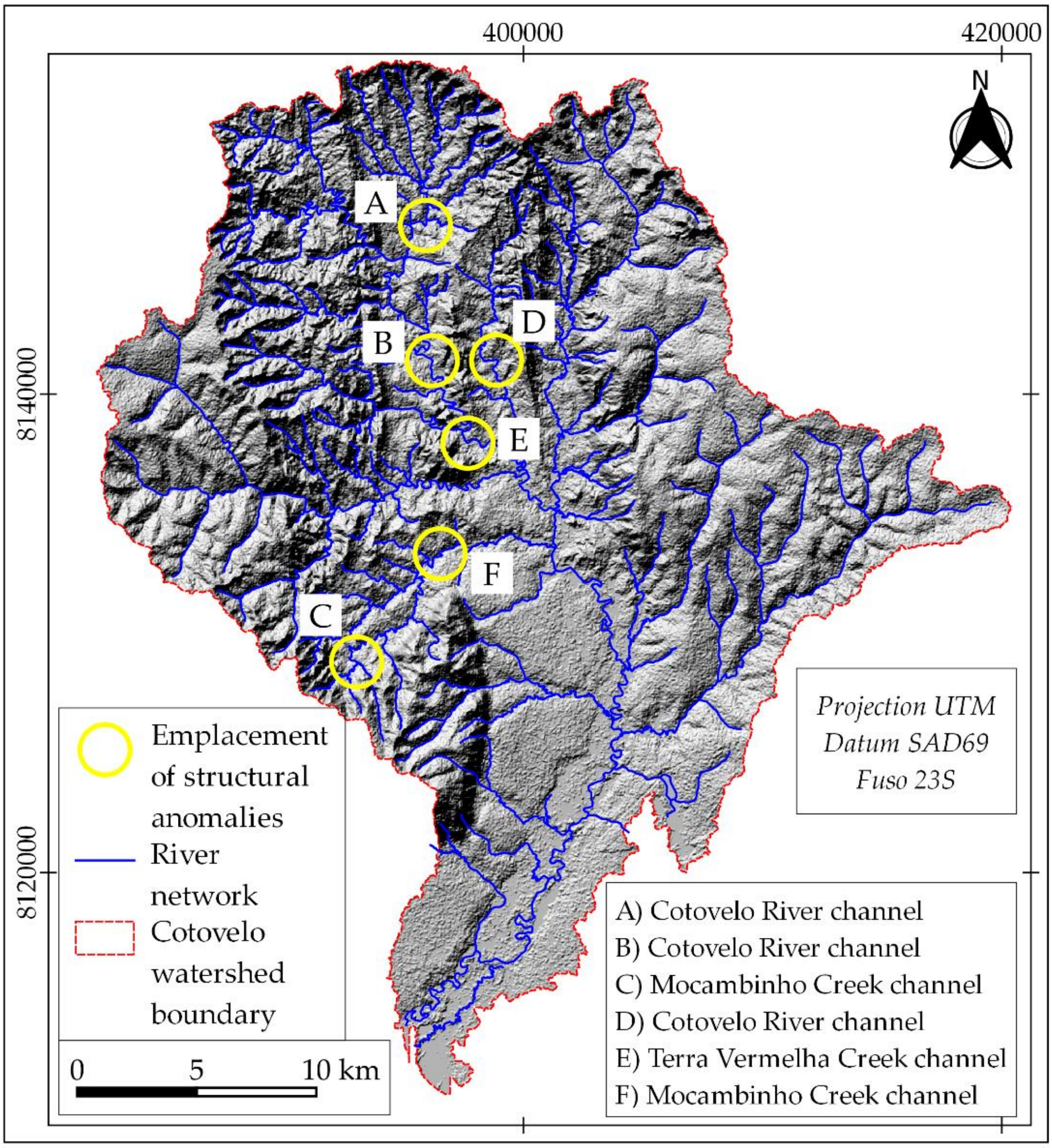

Figure 9. Location of the investigated correlated features between structural and drainage anomalies.

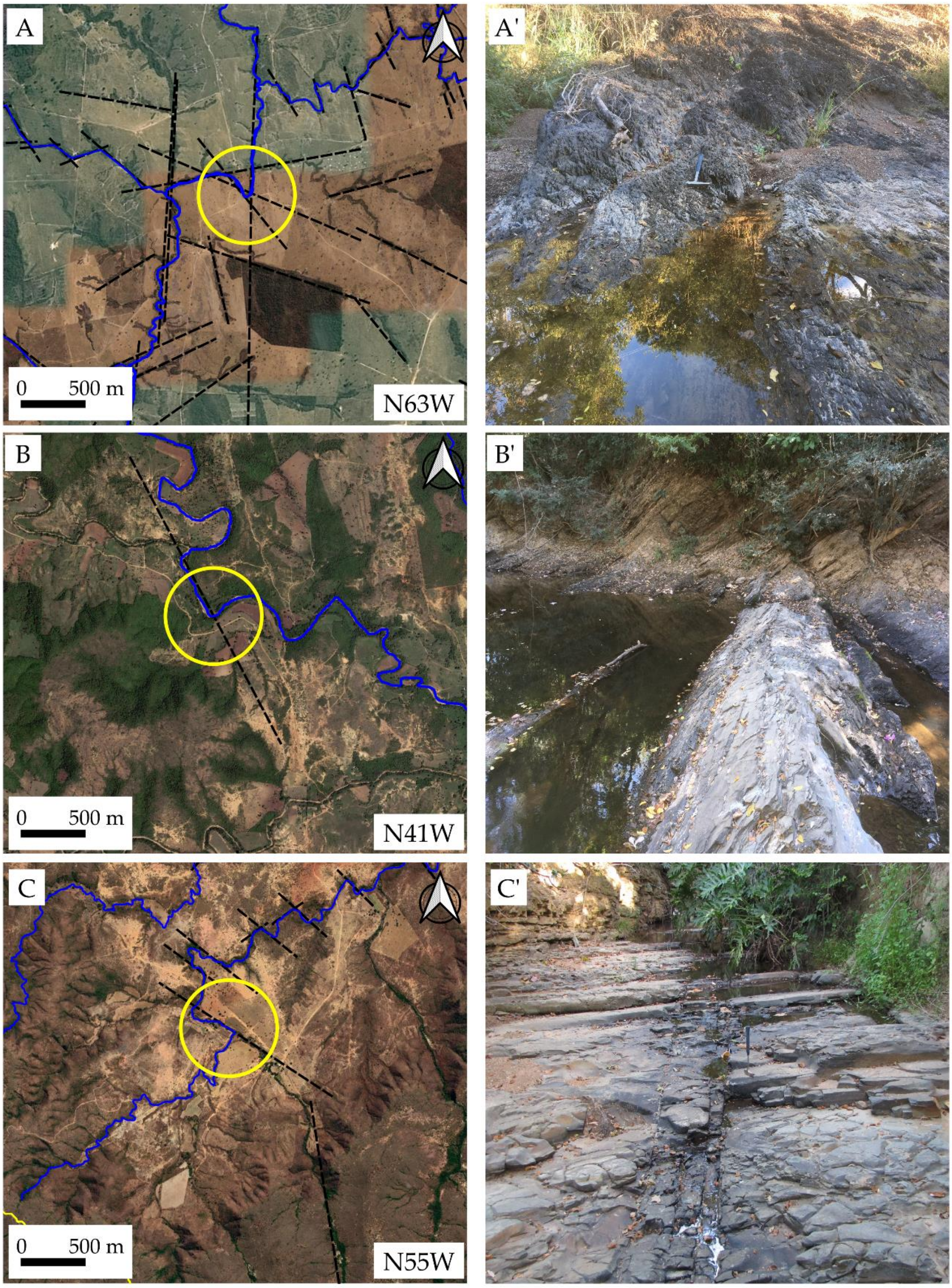

Figure 10. Mapped lineaments plotted on Google Earth satellite images to show the correlation between drainage anomalies and Upper Proterozoic fracture systems. A) Upper course of the Cotovelo River. B) Middle course of the Cotovelo River. C) Upper course of the Mocambinho Creek.

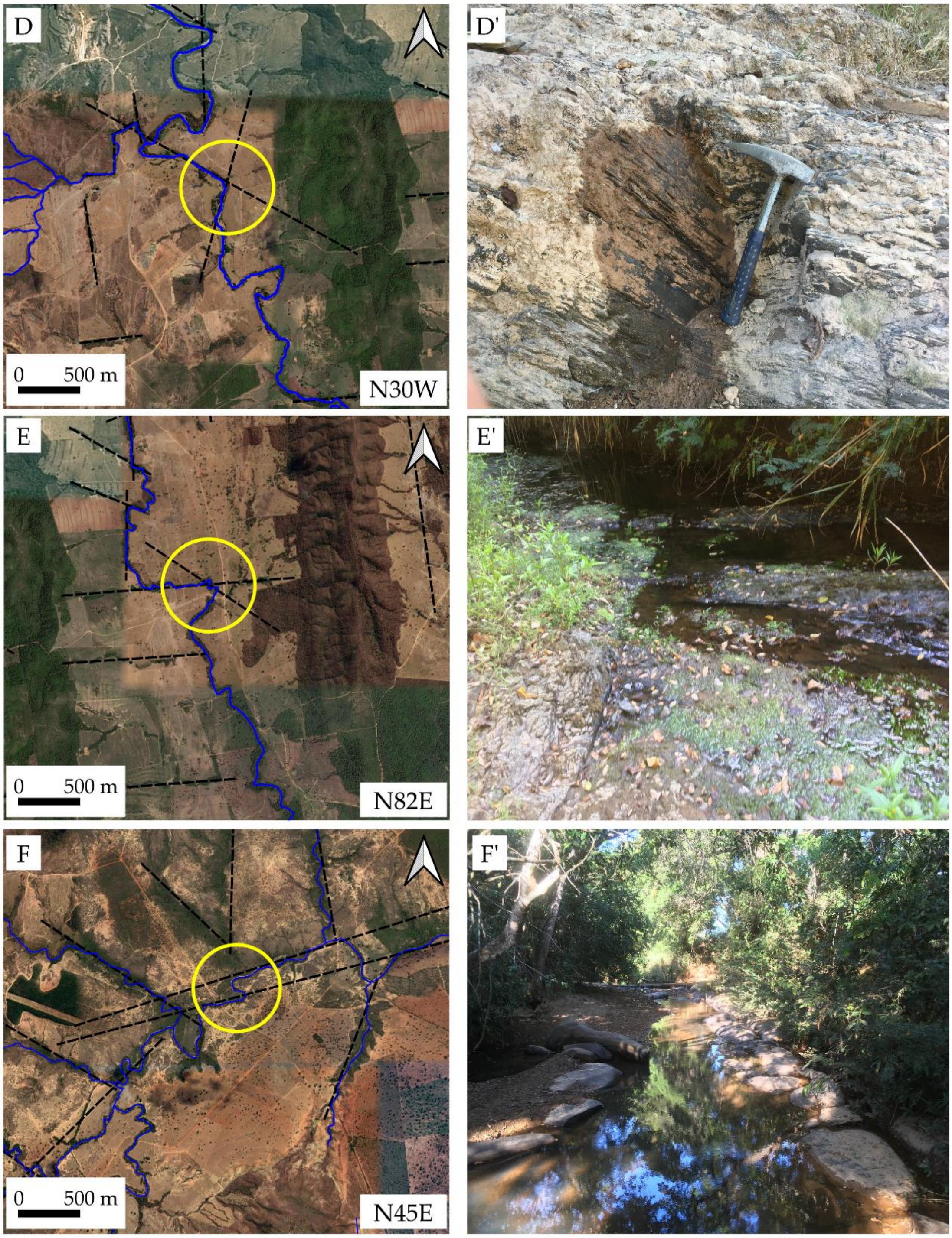

Figure 11. Mapped lineaments plotted on Google Earth satellite images to show the correlation between drainage anomalies and Meso-Cenozoic fracture systems. D) Middle course of the Cotovelo River. E) Middle course of the Terra Vermelha Creek. C) Middle course of the Mocambinho Creek.

Notably, reflecting the dominant directions, the Cotovelo River first flows southeast, following a natural course toward the Paracatu River. Suddenly, entering its low-course floodplain, the river abruptly changes and proceeds in a southwest direction until it joins the Paracatu River, 24.5 km upstream. This abrupt change justified the river name Cotovelo ("elbow", in Portuguese). This relationship between drainage and lineaments is clearly perceived inside the Cotovelo River catchment, particularly for the full length of the left bank tributary valleys (Forquilha, Assapeixe, Caiçara, and Morro Redondo creeks) and the upper course of the right bank tributary valleys (Mocambinho and Cana-brava creeks).

3.2 Local evidences of structural and tectonic influences

Several local and particular pieces of evidence support the hypothesis of structural and tectonic controls of drainage and geomorphic features. First, in the middle course of the Cotovelo River, where channel flows (Cotovelo and tributaries) are fitted to weaker lines of the Paraopeba shear zone, the river network presents anomalous bends, even with right angles and segments with totally reversed flow directions.

Second, the Sono River catchment is a notable NE-oriented feature because the channel courses fits to SW-NE fractures, which can be chronologically correlated with the Meso-Cenozoic tectonic event responsible for the installation of the Abaeté graben, a tectonically controlled subsidising basin contemporary of the Mata da Corda volcanic event, which promoted the ascent of the mantle. The current São Francisco River channel flows adjusted to a SW-NE mapped lineament, which may have represented a reactivated left-lateral strike-slip fault (HASUI; HARALYI, 1991) that marks the southeast border of the Mesozoic graben and still influences the drainage and local morphodynamics.

Third, a feature indicating the structural control of river networks is the conspicuous linearity of the longest channels, interrupted by abrupt bends, such as Prata, Entre-Ribeiros, Carmo, Paracatu, Galho, Areias, and Urucuia rivers. Strait river segments are characteristic features of regional landscapes.

Fourth, the western scarp of the Boqueirão-Serra Geral do Rio Preto Plateau, conspicuously aligned to the NNW-SSE, was fitted to Precambrian fractures/lineaments, thus resembling a normal fault scarp, and it was possibly correlated to the Galena-João Pinheiro-Unaí fault system (BRAGANÇA, 2017).

Fifth, the occurrence of low-magnitude contemporary earthquakes, whose epicentres coincided with Precambrian lineament and fault systems (Galena, João Pinheiro, Unaí, and São Domingos), demonstrate some type of present movement of that fault system.

3.3 River and landscape dynamics

In a broad area, the geomorphologic scenario resulting from a densely fractured basement points to long-term landscape dynamics controlled by remnant erosion and vertical dissection. This is clearly perceptible in prominent regional topographic features, supported by horizontal to sub-horizontal rock strata, with the oldest rock units at the bottom and younger ones at the top, as previously described in the geologic settings.

Moreover, both regional catchments (Paracatu and Urucuia) seem to have evolved by means of remnant erosion because their valleys are fitted to mapped Precambrian weaker lines, which are preferential methods of fluvial dissection. This can be observed in the upper and middle courses of the Urucuia River and different sectors of the Paracatu River. Another relevant element to consider in these catchments is the existence of two different sectors: the low course, a northeastward-oriented sector, and the middle-upper course, a northwestward-oriented sector. In these two sectors, the headward directions were fitted to Precambrian mapped fractures/lineaments. Surprisingly, several Paracatu River tributary springs indicate captured and diverted channels from the Paranaíba River catchment at the south-southwest neighbour. According to a proposed hypothesis (CHERÉM et al., 2014), the Preto River itself was diverted and captured from the same catchment; thus, suggesting that the extremely long length of this channel is an older spring for the Paracatu River that led to the hypothesis that a deep and complex internal rearrangement of the drainage system had occurred.

The geomorphic characteristics are supported by the superimposed drainage in the context of long, slow, and continuous tectonic activity during the Meso-Cenozoic interval. Clues for such interpretations are obtained from the indiscriminate orthogonal dissection of Precambrian reverse faults inside the Preto River catchment, from a similar feature with great geomorphologic expression inside the Conceição River catchment, and from the deep gorge dissected by the Paracatu River, which allows for the crossing of the south-north-aligned topographic obstacle shaped by the Maravilha and the Boqueirão Plateau.

Due to such a structural control, drainage networks exhibit some remarkable parallelism as well as correlate to the most prominent topographic elements. In both cases, there is strong control by the Precambrian NNW-SSE mapped fractures/lineaments followed by a secondary NE-SW direction.

Over a long-term timescale, landscape evolution seems to be controlled by successive alternating processes of active and passive tectonic phenomena, according to the cinematics of the South America plate, which was determined by the Gondwana break-up and Andean tectonics (HASUI, 1990). This slow speed was compatible with superimposed drainage. Specifically, the Preto, Carmo, Prata (middle course), and Cotovelo river networks fitted well to Precambrian shear zones oriented by the NNW-SSE craton-mobile belt contact strip. At the top of the higher SW-NE oriented topographic elements, low-order drainage fitted the Meso-Cenozoic tectonic event weakness lines according to South America plate rotation, which reactivated anisotropies and led to block accommodation. In these cases, the Sono, Santo Antonio, Almas, and Caatinga Rivers are examples of rectilinear fault-adjusted channels (Figure 12).

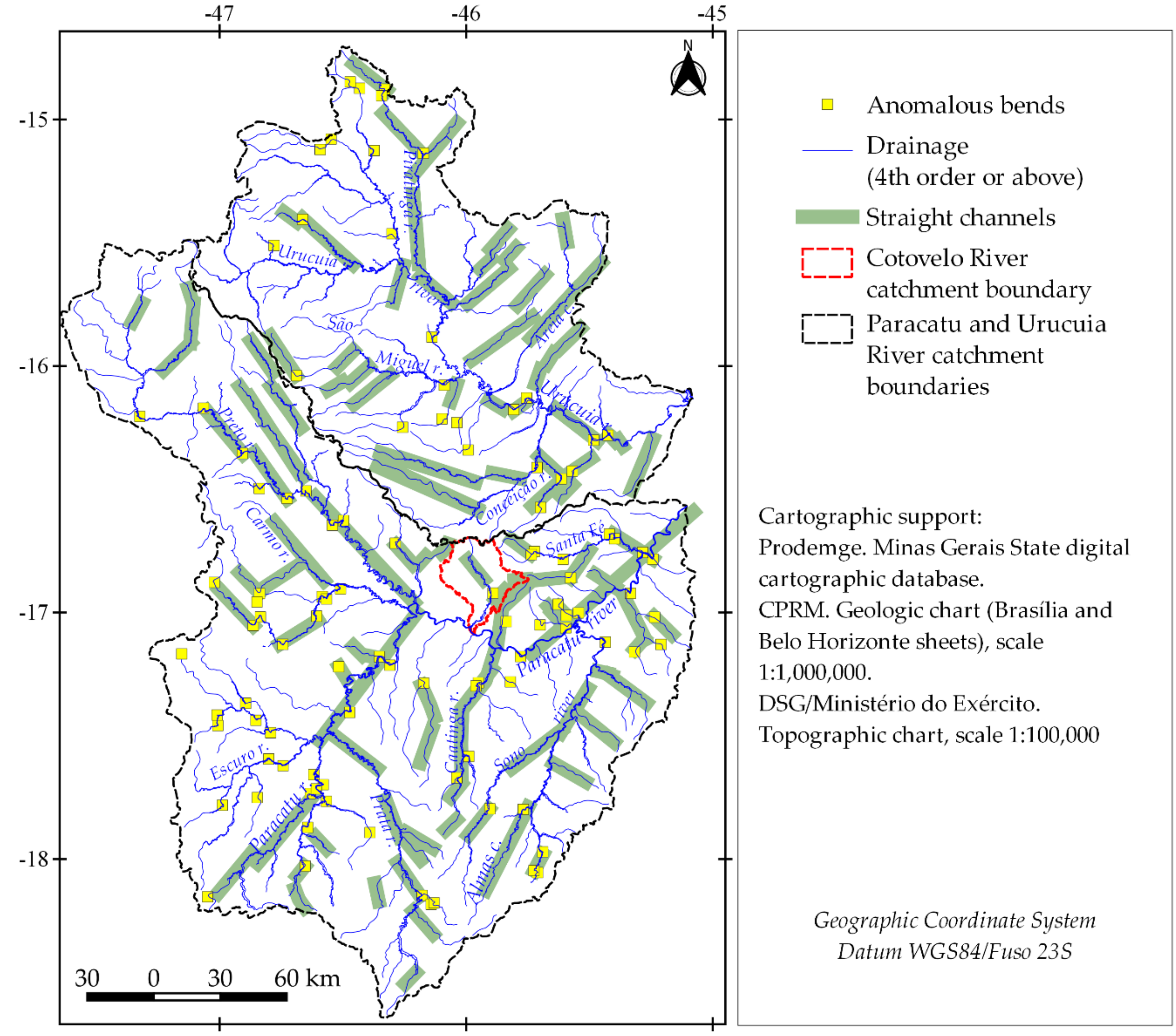

Figure 12. Predominant straight, rectilinear, long channels, and anomalous bends in the Paracatu and Urucuia River catchments.

Anomalous bends interrupt these features, commonly at the juxtaposition of different structural directions. (Modified from BRAGANÇA et al., 2022).These findings strongly suggest that the Paracatu catchment underwent major reorganisation and evolved by remnant erosion, which led to a continuous and progressive increase in the captured areas of nearby catchments. This process started during the Middle to Upper Cretaceous period, probably after the breaking of an endorheic drainage system (VALADÃO, 1998) caused by the preferential fluvial dissection of a reactivated NNW-SSE Precambrian Galena-João Pinheiro-Unaí fault system and their branches crossing the Boqueirão-Maravilha topographic high. The inner landscape evolved through continuous erosive lowering of Cretaceous and Precambrian rocks, which led to the superimposition of rivers to old structures.

4. Conclusion

Numerically representative within the local context, this new vector database made it possible to define at least three relevant arbitrary categories of lineaments for regional morphostructural analyses. Extremely long lineaments (longer than 30 km) oriented to the NNW-SSE can be associated with the Brasiliano structures and indicates contact between the São Francisco Craton and Brasília Mobile Belt. Intermediate-length lineaments (between 10 and 30 km), which were delineated over Mesozoic sandstones and oriented to the SW-NE, documented the Cretaceous-Cenozoic tectonic event. Small- to medium-sized lineaments (less than 10 km) traced over the Upper Cenozoic to Quaternary units were oriented to the SW-NE, NW-SE, and E-W and probably follow the tectonic reactivation potentially induced by the opening of the South Atlantic and South America plates, which spread to the west.

On the western bank of the São Francisco River in northwestern Minas Gerais State, major crustal tectonic features, such as the Traçadal-Três Marias-São Domingos and Galena-João Pinheiro-Unaí fault systems and their branches, controlled the long-term geomorphological dynamics. Structurally controlled sedimentary basins, such as the Abaeté Upper Mesozoic sedimentary sub-basin and the Unaí Crests ridge and valley province, support this scenario. Furthermore, the parallel to sub-parallel drainage pattern presented two preferential directions: a Proterozoic NNW-SSE pattern and Meso-Cenozoic SW-NE pattern. Some of these Precambrian and Meso-Cenozoic faults have been reactivated, probably as small normal faults, with vertical offsets controlling the current deep and narrow valleys.

Moreover, remarkable directional correlations are observed between the mapped structural directions, partly due of the existence of two large patterns that control the hydrogeomorphological landscape. On a large scale, large rivers such as Paracatu, Preto, Sono, Urucuia, and São Francisco are controlled by fault systems and major crustal lineaments. Morphostructures, such as the Unaí Crest and Boqueirão-Geral do Rio Preto Plateau, present the same behaviour and resemble features related to the large structural pattern of the Tocantins and São Francisco Precambrian provinces. This geomorphic pattern is related to the two previous crustal weak conditions: the NNW-SSE structural contact between the craton and mobile belt, which is physiographically expressed in the western deeply deformed cratonic coverage domain; and the SW-NE cratonic structural directions present in the less-deformed central cratonic coverage domains, which can be better observed in the Paracatu and Urucuia river catchments.

At the local scale, structure and drainage patterns are subject to another controlling event, the Meso-Cenozoic tectonic event. Moreover, recent drainage superimposed on the Paraopeba subgroup within the Cotovelo River catchment showed strong geomorphic and fluvial evidence of such control. The shorter river channels and landforms fit to the NE-SW structural direction, such as some meandering-like segments, thus revealing entrenched rivers.

Similar reasoning can be applied to river lengths. These two main trends are recognisable in the current pattern of the drainage network. The longest courses are fitted to the older direction with shortest rivers (mainly springs and low-order segments) adapted to the Meso-Cenozoic structures. Furthermore, three diversified shapes of river networks form regionally due to the juxtaposition of different structural patterns and lithological types, e.g., dendritic to sub-dendritic, orthogonal or angular/trellis, and parallel to sub-parallel. Overall, the regional drainage responds to the global process of intraplate stress, which reactivated Precambrian and Gondwanide anisotropies that control the Upper Cenozoic morphotectonic background at the western edge of the São Francisco Craton/Brazilian Atlantic shield.

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